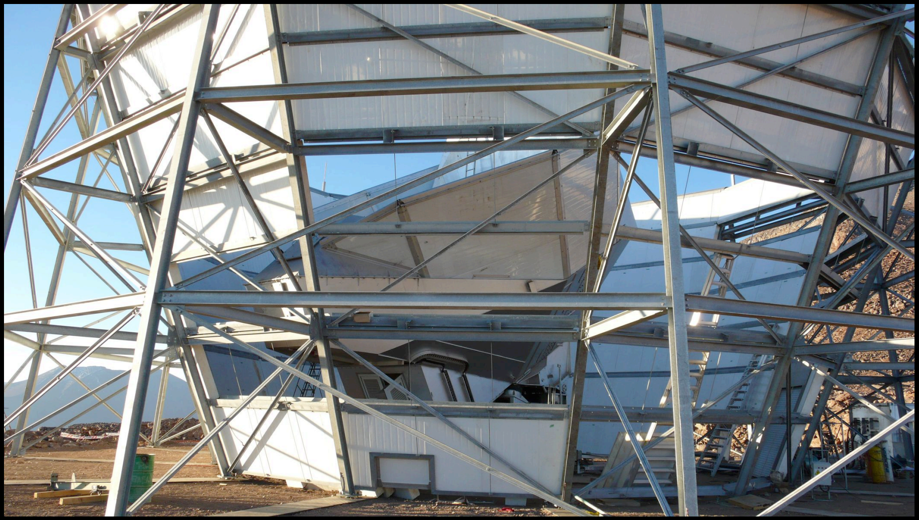
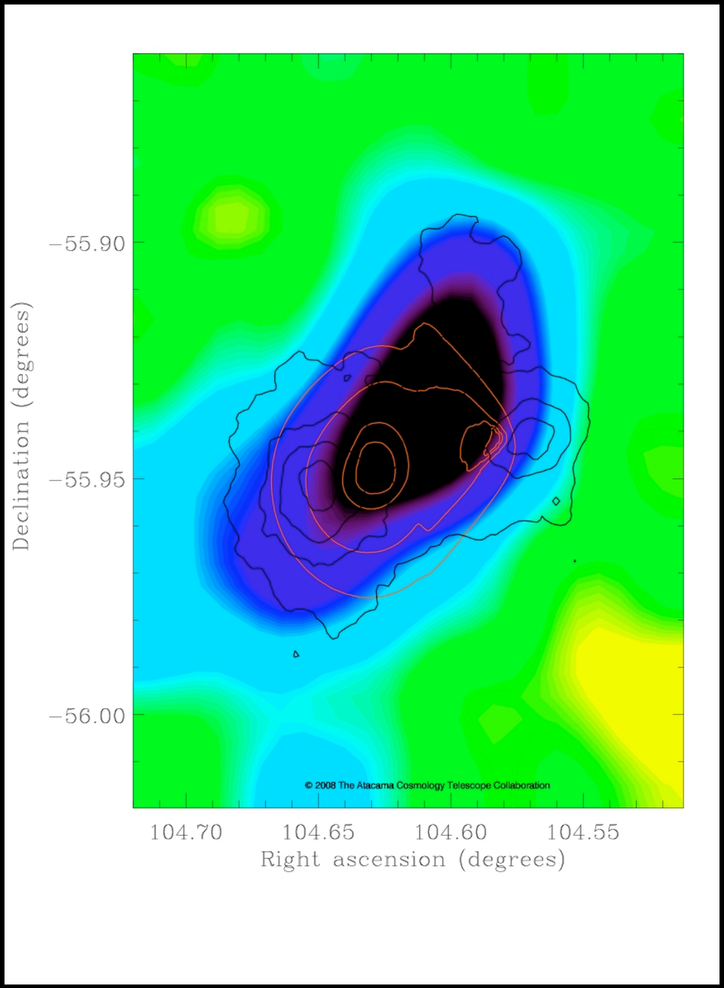
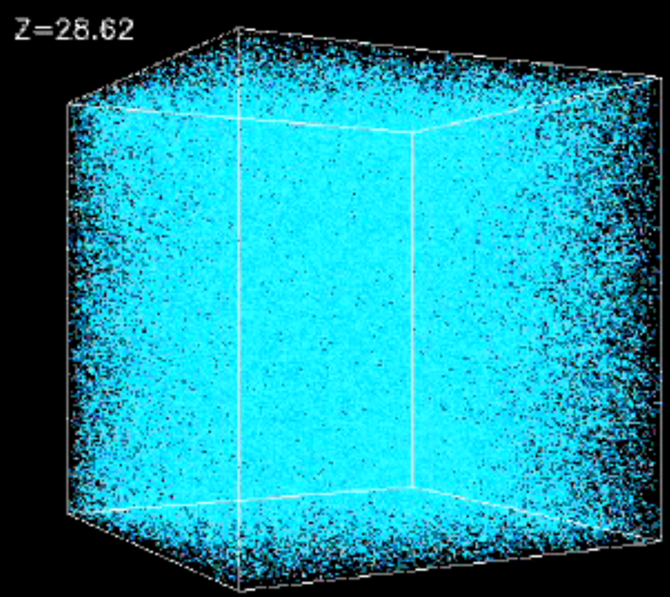
The SZ effect: Surveys and Cosmology





Michele Limon Columbia University

Structure Formation

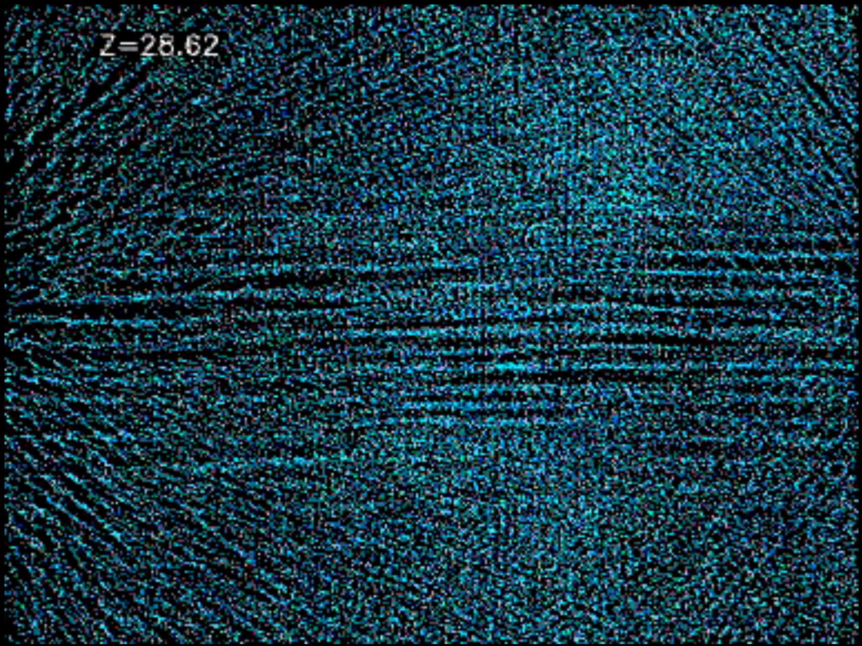


- Standard ΛCDM Model
- Box Size 43 Mpc^3
- $30 > z > 0$

In typical structure formation scenarios, low mass clusters emerge in significant numbers at z~2-3

http://cosmicweb.uchicago.edu/filaments.html

Group/Cluster Formation



- Standard ΛCDM Model
- Box Size 4.3 Mpc^3
- $30 > z > 0$

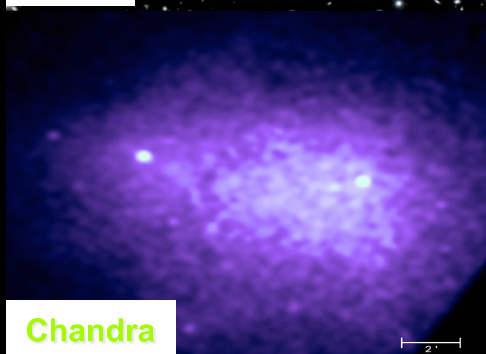
http://cosmicweb.uchicago.edu/group.html

Galaxy Clusters

Galaxies

$M_{gal} \approx 0.02\ M_{tot}$ — Early types

$N_{gal} \approx 10 - 1000$ — Poor groups – rich clusters



Gas

$M_{gas} \approx 0.1\ M_{tot}$ — Heated by infall

$T_{gas} \approx (1\text{-}15)\ keV$

Galaxy Cluster Abell 2218 HST • WFPC2
NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

Dark Matter

$M_{tot} \approx 10^{14} - 10^{15}\ Solar\ Masses$

$R \approx 1\ Mpc$

Why Clusters

- Theory:

  Clusters relatively simple objects. Evolution of massive cluster abundance determined by gravity. Clusters straddle the epoch of dark energy domination $0<z<3$.

- Why Do We Need Yet Another Cosmological Probe?

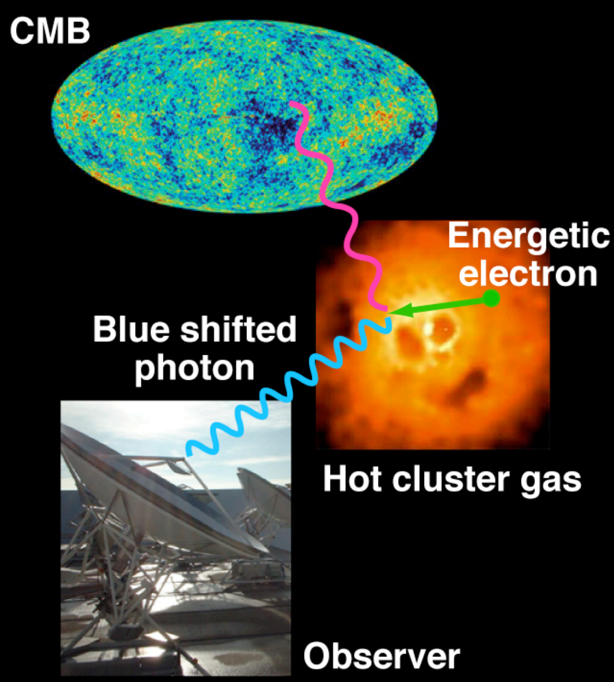
  - Degeneracies differ from CMB, SNe, Galaxies
  - Systematics are different
  - Unique exponential dependence
  - Modelability

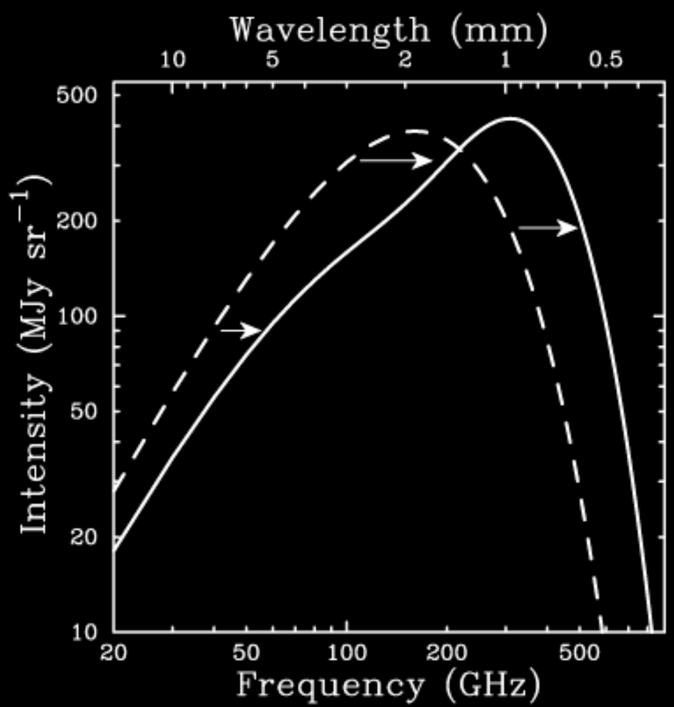
Adapted from Zoltan Haiman

How to find Clusters

- Optical/IR imaging: Early type galaxy colors (e.g., darkCAM, DES, ISCS, LSST, Pan-starrs, RCS1&2 ,...)
  - Good contrast
  - Relation to mass
- X-ray imaging: L_x from hot gas (e.g., review by Rosati et al. 2002, XCS)
  - Good contrast
  - T tightly correlated to mass
  - All-sky surveys - shallow
  - Deeper serendipitous - limited area, inhomogeneous
- Weak lensing: shear/aperture mass (e.g., DUNE, JDEM)
  - Direct relation to mass
  - Projection effect
- SZ Survey

Sunyaev-Zel'dovic Effect

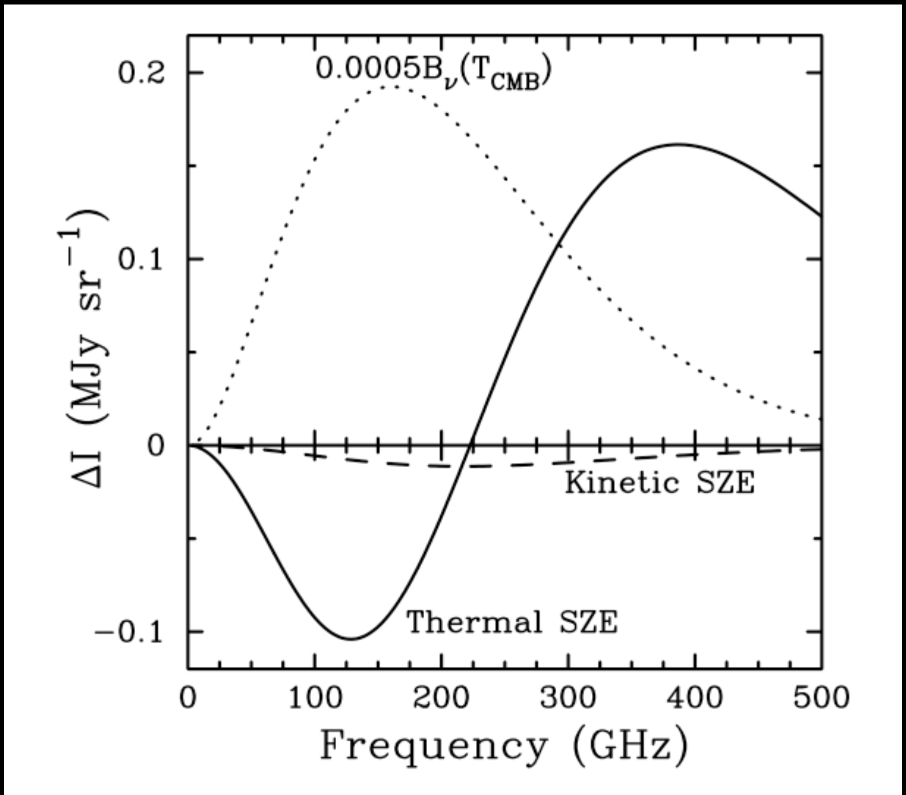




In the Rayleigh -Jeans Regime:

$$\frac{\Delta T_{\mathrm{SZ}}}{T_{\mathrm{CMB}}} = -2\frac{\sigma_{\mathrm{T}} k_{\mathrm{B}}}{m_{\mathrm{e}} c^2} \int n_{\mathrm{e}} T_{\mathrm{e}} dl$$

Thermal & Kinetic SZ Effect



For T_{cmb} =2.726K

λ_- = 2.34 mm ν_- = 128 GHz

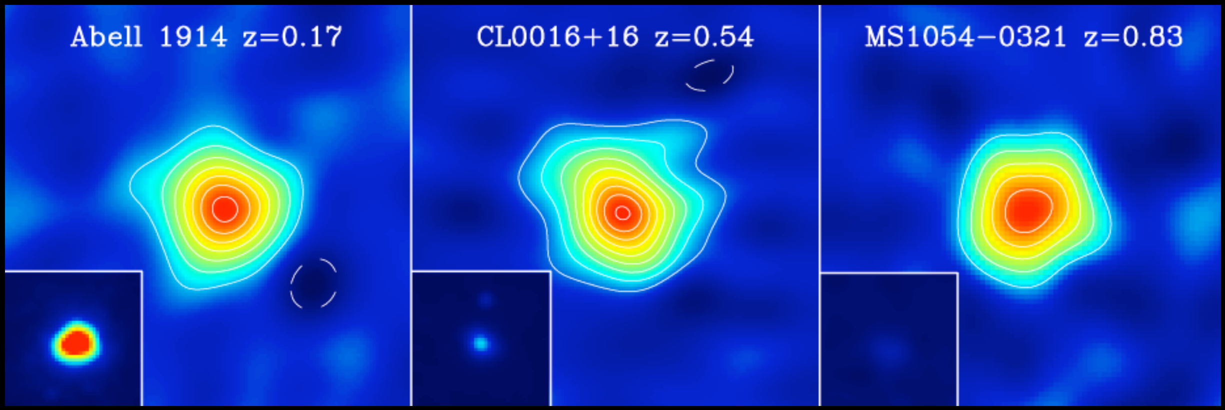
λ_o = 1.38 mm ν_o = 218 GHz

λ_+ = 0.80 mm ν_+ = 370 GHz

Thermal and kinetic SZ effect for a cluster with a peculiar velocity of 500 km s^{-1} (Carlstrom et al. 2002).

SZ Effect: why it is so nice

SZ contours are 0.75 μK and X-ray scales are the same.

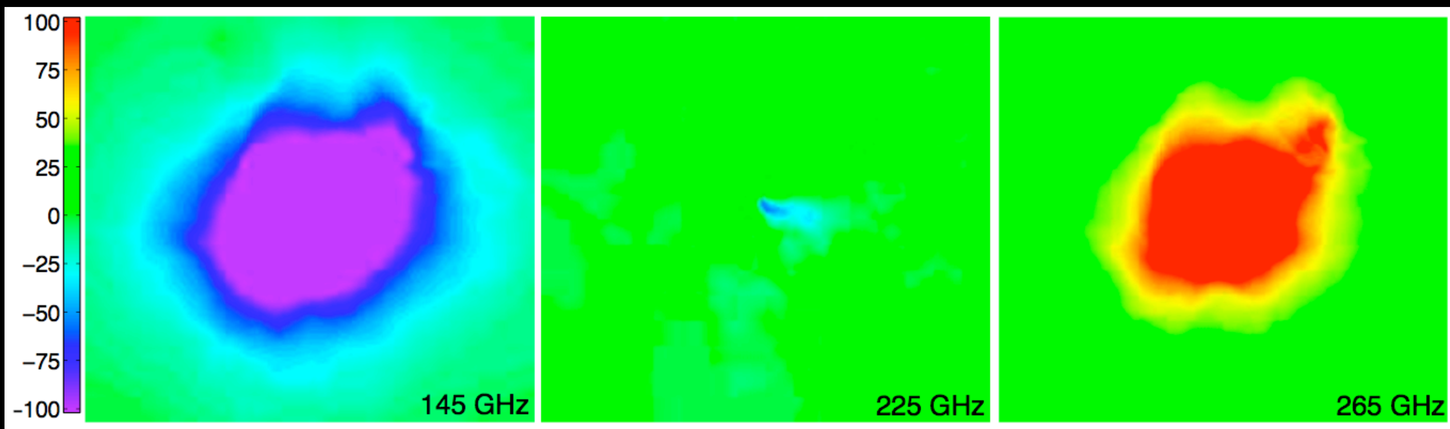


SZ and X-ray maps (insert). Mohr 2002

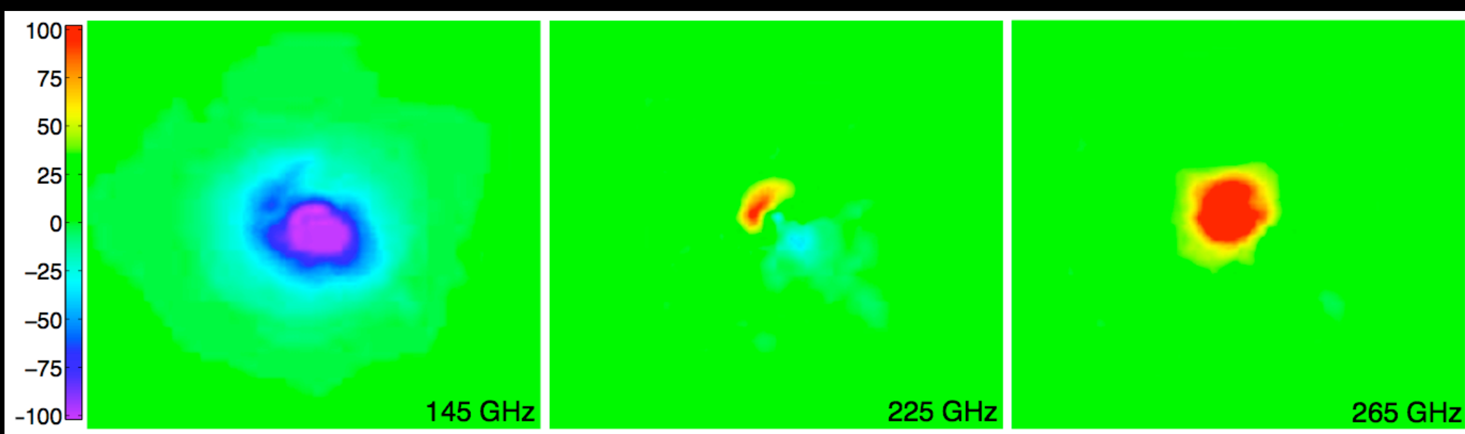
Z = 0.17 Z = 0.54 Z = 0.83

1) The very distinct spectral signature
2) Measures the total thermal content of the cluster
3) Temperature decrement more or less redshift independent
4) Less susceptible to complicated cluster substructure, core physics (proportional to density and not density squared as in Xrays)

SZ Spectral Signature

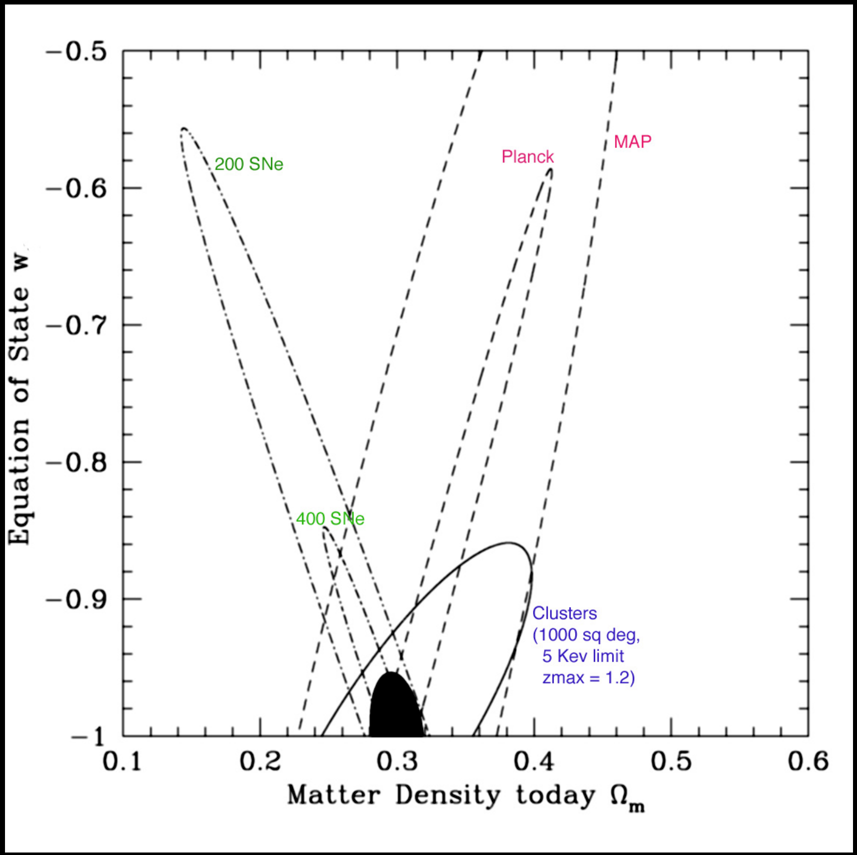


$M = 10^{15} M_\odot$
$T = 9$ keV
$z = 0.43$



$M = 2{\times}10^{14} M_\odot$
$T = 3$ keV
$z = 0.43$

Potential for different methods to constrain "w"



Cluster Surveys are complementary to already well established cosmological probes

Levine, Shultz & White 2002

Sensitivity of Cluster Redshift Distribution to Dark Energy Equation of State

Increasing **w** keeping Ω_E fixed has the following effects:

- It decreases volume surveyed
- It decreases growth rate of perturbations

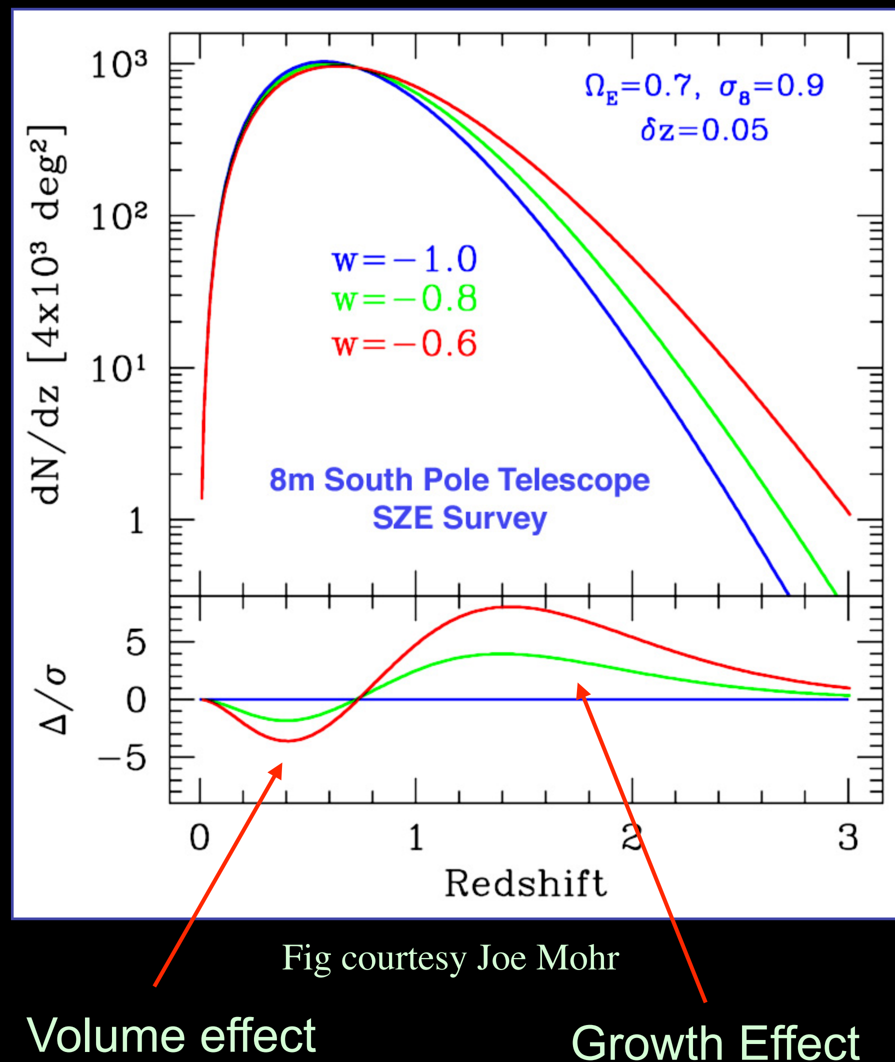


Fig courtesy Joe Mohr

Clusters Surveys

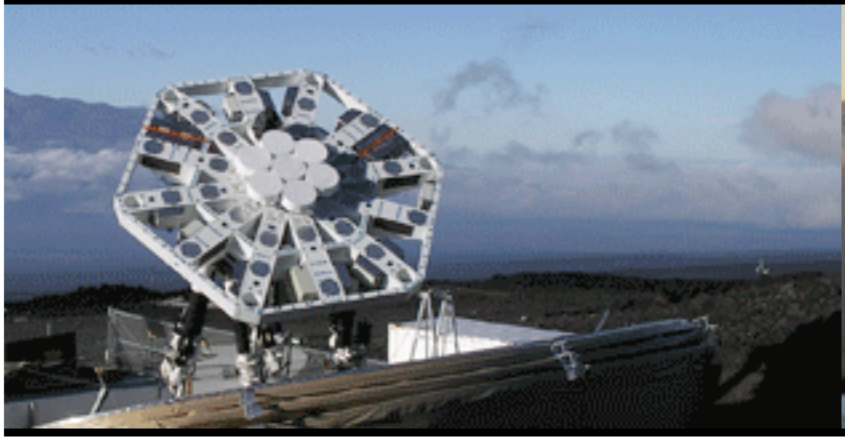
- Interferometers: ~10-100 sq. deg.
  - Arcminute MicroKelvin Imager (AMI) (in operation) first image: astro-ph/0509215
    - 10 new antennas (3.7m) + Ryle Telescope (12.8m), 13.5 – 18 GHz,
  - Array for Microwave Background Anisotropy (AMIBA)
    - 19 antennas (0.3m), 90 GHz, Mauna Loa Hawaii
  - SZ Array (in operation)
    - 8 antennas (3.5m), 30 GHz + 90GHz follow-up, OVRO + BIMA = CARMA
- Bolometer arrays: ~100-4000 sq. deg.
  - ACBAR: 4 band-4element array at South Pole (in operation)
  - BOLOCAM: 150 element array CSO Mauna Kea (in operation)
  - APEX: ALMA prototype, 300 element array Llano de Chajnantor (Chile) (in operation)
  - ACT: Atacama plateau, 3 x 1000 element array Cerro Toco (Chile) (in operation)
  - SPT: 10m dish, 1000 element array South Pole (in operation)
- Planck: ~40000 sq. deg. = all-sky
  - ~10,000 clusters L2 launch 2008/2009

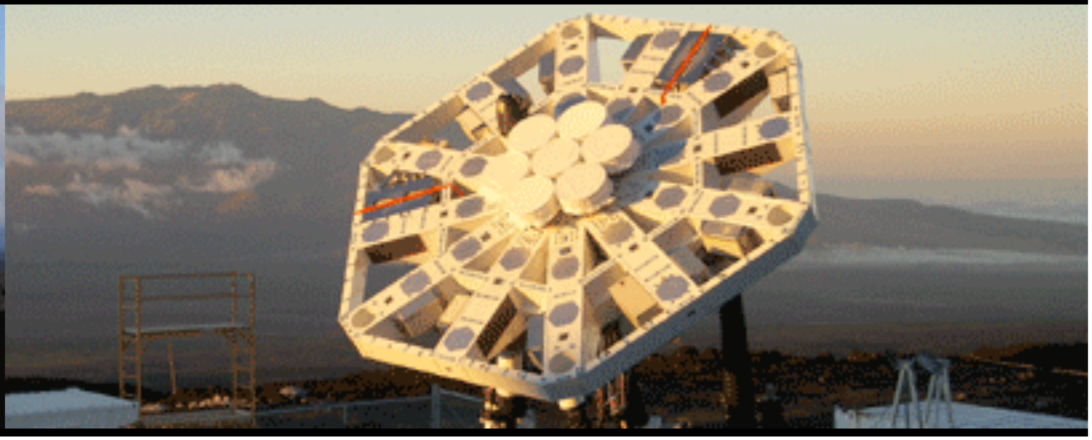
AMI

Sub-array	AMI-SA	AMI-LA
Primary dish diameter	3.7 m	12.8 m
Antenna efficiency	0.75	.067
Number of antennas	10	8
Number of baselines	45	28
Range of baseline lengths	4 – 20 m	18 – 120 m
Primary beam (FWHM at 15 GHz)	18’	5.5’
Observing frequency	13.5 – 18 GHZ	
Effective Bandwidth	4.5 GHz	
Number of frequency channels	6	
Bandwidth of each freq. channel	0.75	
System temperature (zenith)	25 k	
Polarization measured	I + Q	
Site	MRAO, Cambridge UK	
Flux sensitivity	30 mJy $s^{-1/2}$	3 mJy $s^{-1/2}$

AMIBA

AMiBA Spec			
Dual-channel receiver	MMIC; L and R	Platform	6 m configurable; carbon fiber
Operation frequency	86-102 GHz	Correlator	analog (bandwidth 16 GHz)
Site	Mauna Loa, Big Island, Hawaii (3400 m in elevation)		
Mounting system	Hexapod (±30° in polarization; 30° - 90° in elevation)		
7-element (2006-2008)			
Antenna	60-cm Cassegrain; carbon fiber	Synthesized resolution	6 arcmin
FOV	23 arcmin	Observation type	targeted
13-element (2009-)			
Antenna	120-cm Cassegrain; carbon fiber	Synthesized resolution	2 arcmin
FOV	11 arcmin	Observation type	targeted and survey





SZA

http://calvin.phys.columbia.edu/group_web/sza.html

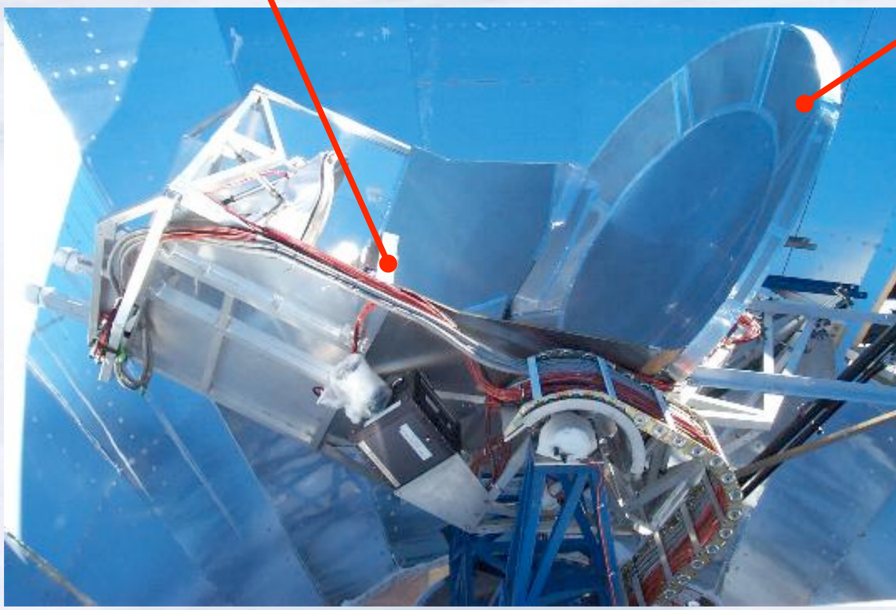
http://astro.uchicago.edu/sza/

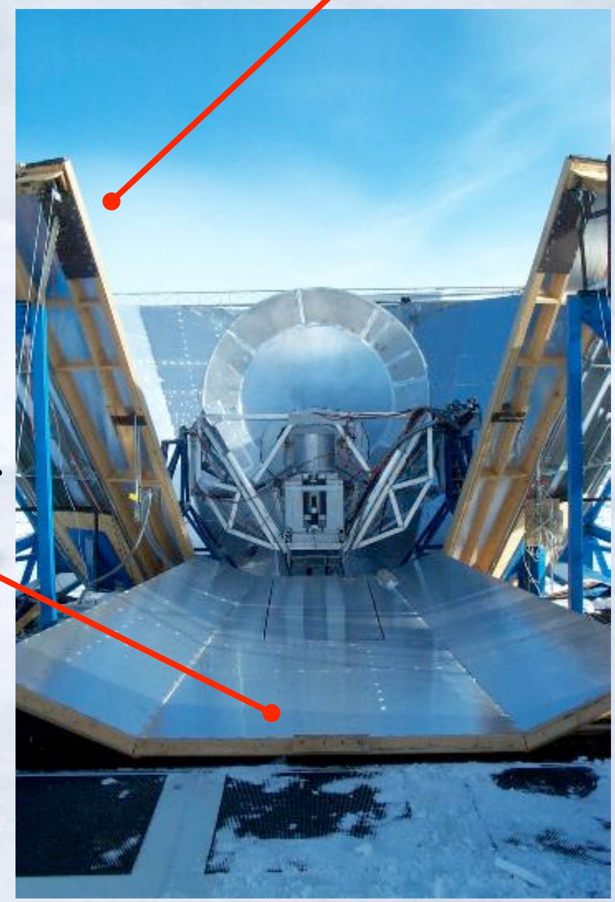
ACBAR operates on the 2m Viper Telescope

Chopping tertiary mirror

Skirt reflects primary spill-over to sky.

Ground shield blocks emission from EL< 25°.





Large AZ chop (~3°)
+ small beams (~4-5′)

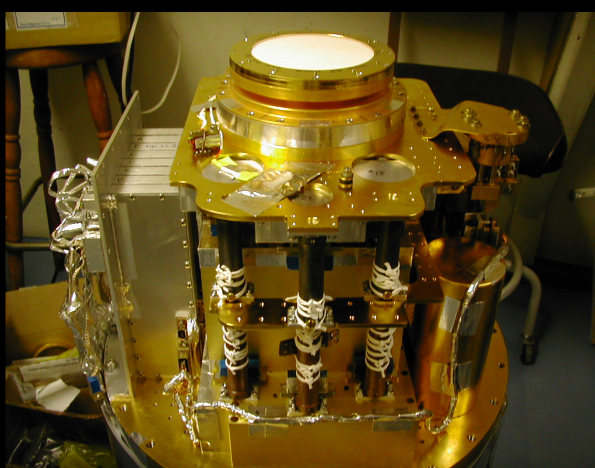
= broad ℓ-space coverage (~75 < ℓ < 3000) *and* sensitivity to clusters over a wide redshift range

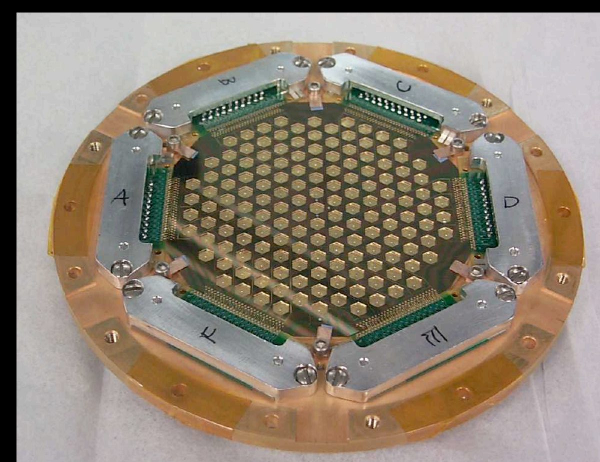
Panel lowers for low-EL observations

http://cosmology.berkeley.edu/group/swlh/acbar/

Bolocam

- Observes at Caltech Submillimeter Observatory   (10.4 m dish)
- Hexagonal array of 144 bolometers
- Array has a 7.5’ field-of-view with individual beam sizes of 30” FWHM
- Sensitivity from the ground limited by temporal water vapor fluctuations
- False detection rate is non-negligible





http://www.cso.caltech.edu/bolocam

ACT: Atacama Cosmology Telescope

- 6 Meter Aperture
- Low Ground Pickup (< 20μK dc)
- No Moving Optics
- Remote Controlled
- Flexible Focal Plane
- Near the ALMA Site

APEX-SZ: Atacama Pathfinder Experiment

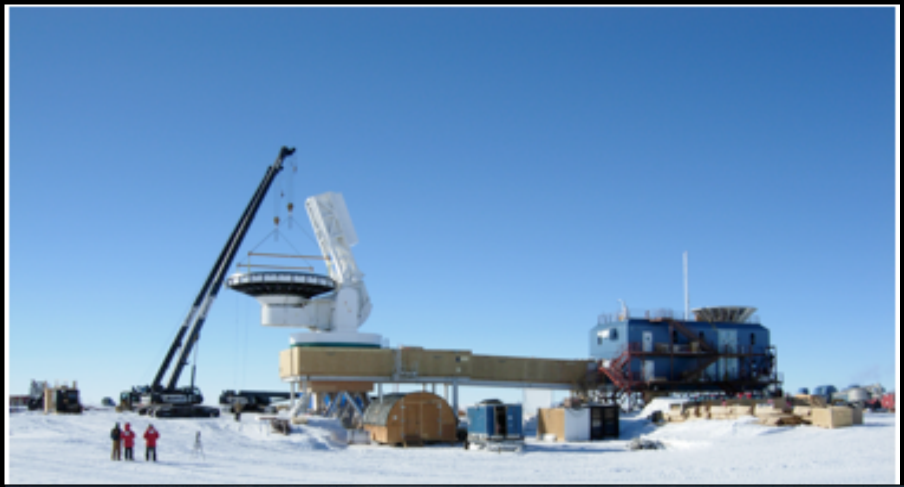
UC Berkeley/LBNL,
MPI-Bonn/Munich,
Cardiff

- 16,500 feet in Chilean Andes.
- 12m on-axis ALMA prototype

Berkeley SZ Receiver:

- 330 Bolometer array
- 25% telescope time
- Could discover 4000 Clusters/2yrs
  - Mass limit > $4x10^{14}$ M_0
- First Light Fall 2004
- Observations in progress

SPT: South Pole Telescope



First light achieved with the 10m South Pole Telescope, February 16, 2007.

•Maps of Jupiter made, showing telescope and optics working as designed.

• Plan to do 4,000 sq. degree survey at 90, 150 and 220 GHz at ~ arc minute resolution.

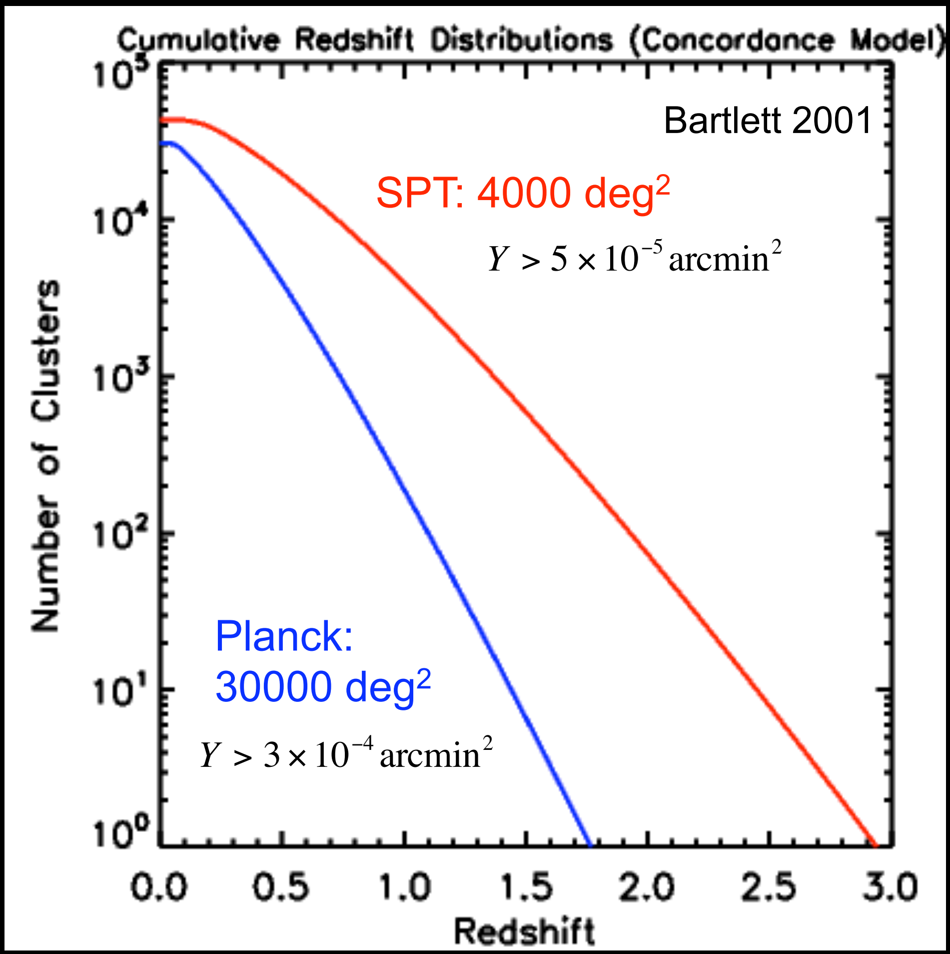
The SPT is a collaboration between the U of Chicago, UC Berkley, Case Western Reserve University, U of Illinois, and Smithsonian Astrophysical Observatory

How many clusters?

Name	Frequency (GHz)	Beam FWHM (arcmin)	Noise (μK/beam)	S/N=5 (deg^{-2})	Total
AMI	15	1.5	8	16	~150
SPT	150	1	10	11	~40000
	220	0.7	60		
	275	0.6	100		
ACT	145	1.7	1.7	40	~4000
	225	1.1	4.8		
	265	0.93	7.8		
Planck	143	7.1	6	0.35	~10,000
	217	5	13		
	353	5	40		

Adapted from J. Bartlett

Clusters at high z



~100s of Planck clusters at z>1 (unresolved)

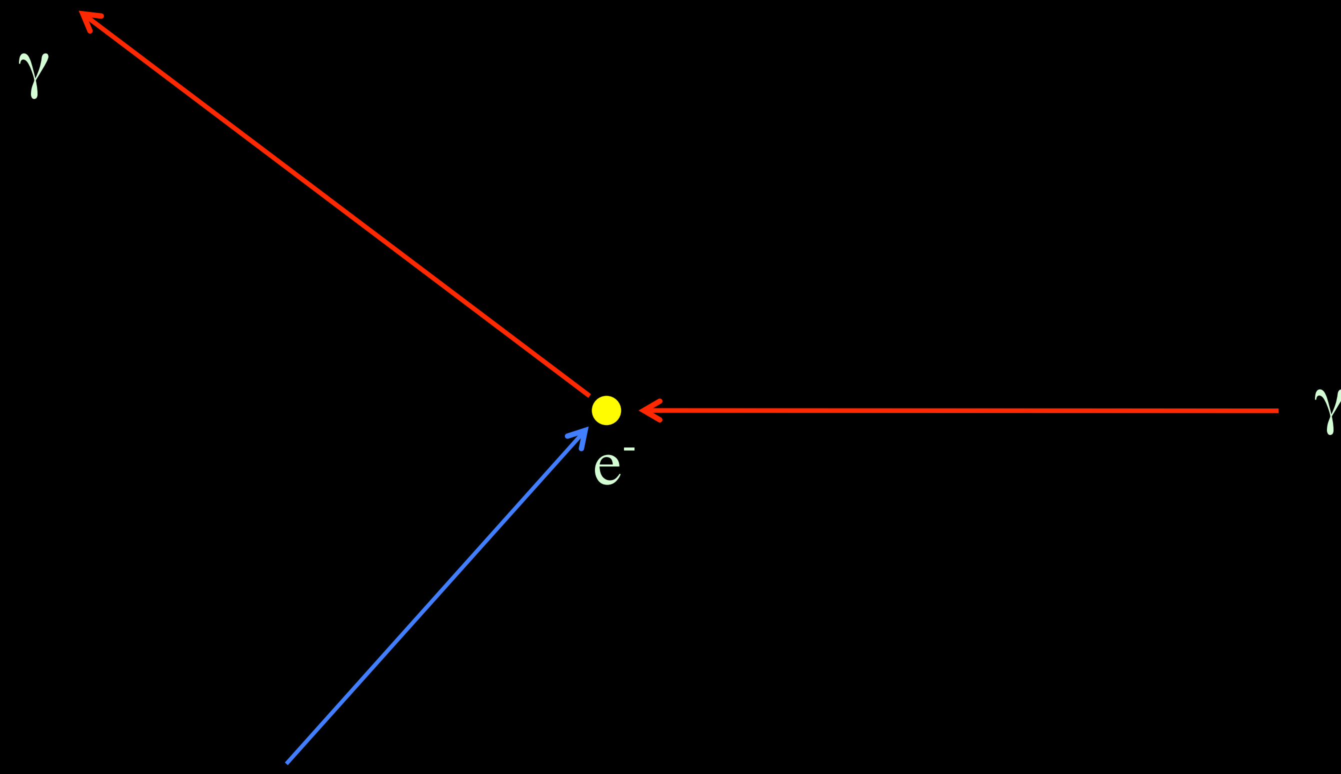
~1000s of SPT clusters at z>1

Adapted from J. Bartlett

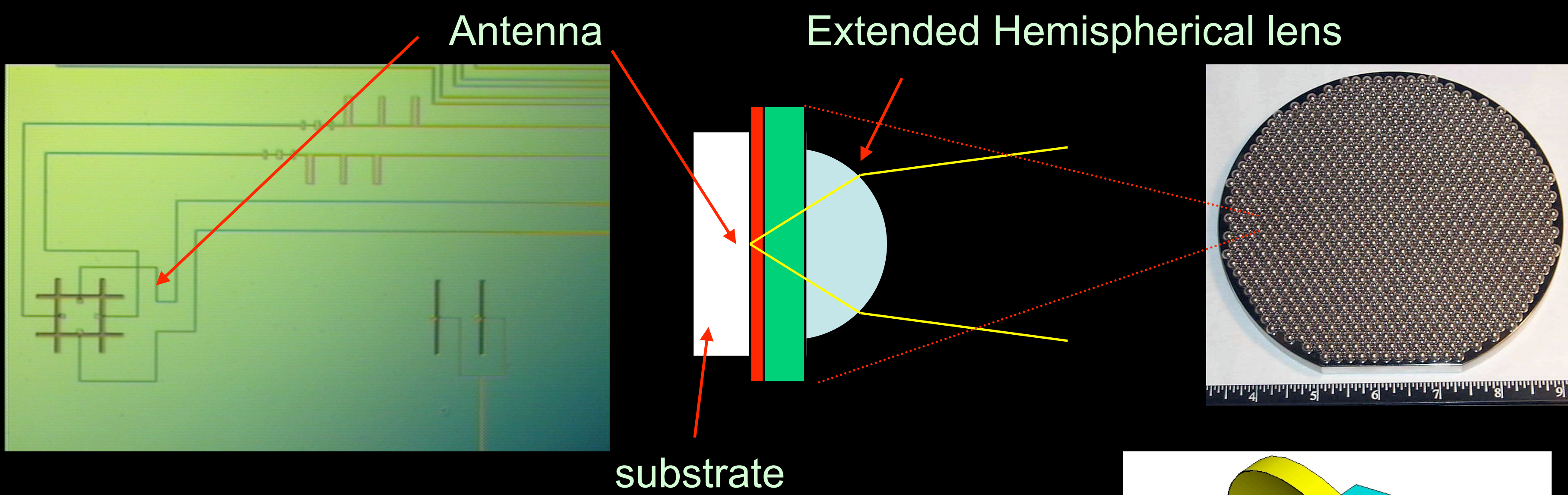
Summary

- *Upcoming large yield cluster surveys would unveil a new era of doing cosmology with clusters. It has the promise to become 4th pillar of precision cosmology along with CMB, SNe and weak lensing.*
- *These surveys provide us an opportunity to probe the enigma of dark energy with high precision, while at the same time probing the high l structure of the CMB*

Sunyaev-Zel'dovic Effect

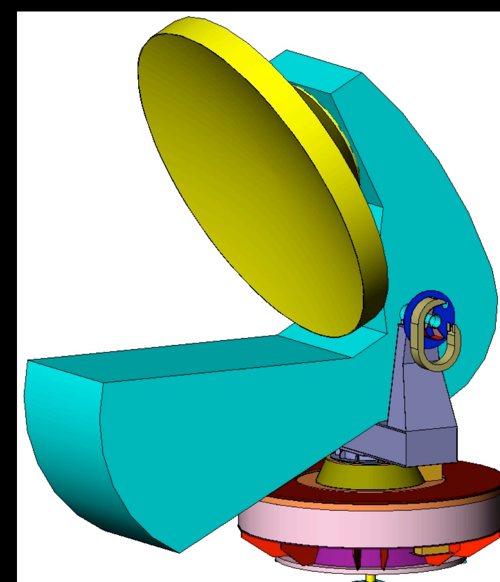


PolarBear

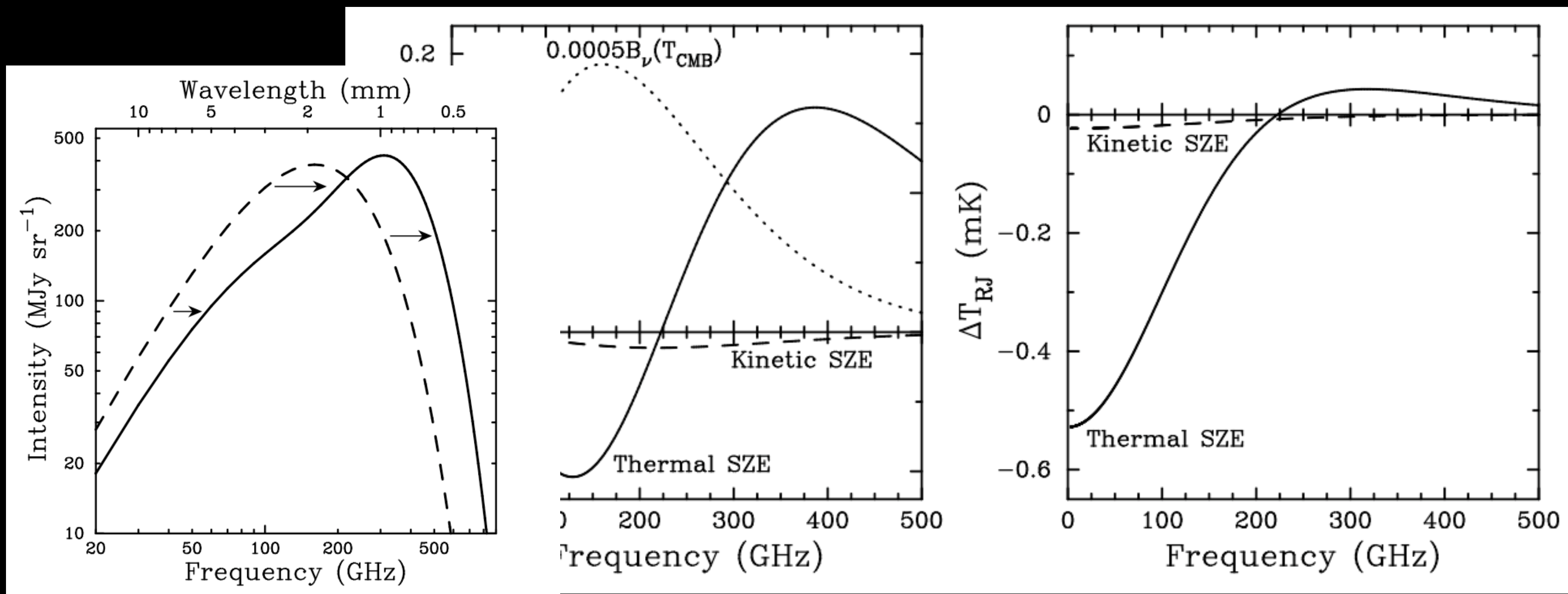


Ground-Based 3 meter Telescope at
White Mountain CA

- Characterize E-modes
- Search for B-modes



Why Clusters



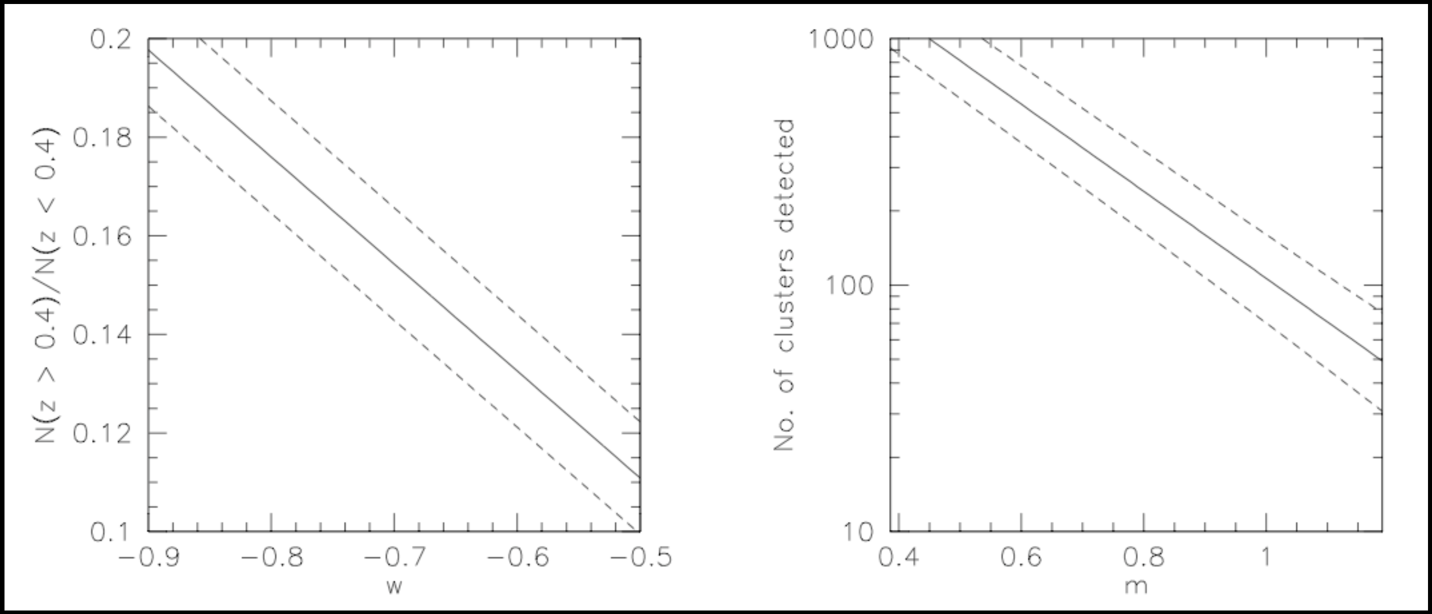
SZ Effect: Equation

In the Rayleigh -Jeans Regime:

$$\frac{\Delta T_{\mathrm{SZ}}}{T_{\mathrm{CMB}}} = -2\frac{\sigma_{\mathrm{T}} k_{\mathrm{B}}}{m_{\mathrm{e}} c^2} \int n_{\mathrm{e}} T_{\mathrm{e}} dl$$

- The SZ temperature is a line-of-sight pressure integral of electron density (n_e) and gas temperature (T_e).
- The SZ temperature decrement is redshift-independent: When the CMB photons interacted with the cluster, $T_{\mathrm{CMB}}(z)$ was hotter and this compensates for cosmological dimming.

Why Clusters



Why Clusters

- SZ effect ideally suited for cluster surveying
  - Efficient at high z
  - Roughly uniform mass selection out to z>1
  - Expectations 2007-2010: **10s => 1000s @ z>1**
    - o Interferometers ~ 100 (**~10% at z>1**)
    - o Bolometer cameras ~ 1,000 - 10,000 (**~10% at z>1**)
    - o Planck ~10,000 all sky (**~1% at z>1**)